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# **An Evaluation of Two Feedback Versions of the Ceres-Maize Model**

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AN EVALUATION OF TWO FEEDBACK VERSIONS OF THE CERES-  
 MAIZE MODEL. By William C. Iwig and Benjamin F. Klugh, Jr.,  
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## ABSTRACT

Two feedback versions of the CERES-Maize model were developed. The first version forces the modeled values of leaf number and vegetative biomass to statistically match measurements of the observed corn crop made on any day prior to tasseling. The second version performs additional adjustments to the modeled yield components of kernels per plant and kernel weight based on the feedback data. The objective of feedback is to improve model estimates of final yield for the observed crop. Analyses using six test data sets indicated that only the second feedback version produced significantly improved estimates of yield and kernel weight and that neither version produced improved estimates of kernels per plant.

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## SUMMARY

This report describes two feedback versions of the CERES-Maize crop simulation model. The major objective of feedback is to improve the accuracy of the final yield estimate from the model for a particular crop data set. Analyses on six test data sets indicated that adjusting only simulated vegetative growth and development through feedback did not provide improved estimates of modeled yield or yield components. In one data set, the first feedback procedure produced a 60% biomass reduction, but yield changed less than 10%. Significantly improved estimates of yield and kernel weight were only obtained when additional adjustments were made to the yield components in a second feedback version. Neither of the feedback versions produced improved estimates of kernels per plant.

Feedback is a technique used to provide more accurate yield forecasts or estimates for a specific sample plot from a crop simulation model. The modeled growth and development is forced to closely approximate (statistically equal) observed crop characteristics at a point in time. The first feedback approach statistically matches the number of leaves and vegetative biomass of the observed crop on any date prior to tasseling to several internal model variables using an iterative adjustment procedure. The second feedback version also uses one of these internal variables to directly adjust modeled yield components.

These two feedback versions are designed to utilize data collected from only one feedback date prior to the end of leaf growth. The feedback date is the date that field measurements were taken. Analysis was conducted to determine when feedback data should be collected to provide the best information for correcting modeled growth. The model is only forced to statistically equal the observed characteristics on the feedback date, therefore it is desirable to have the feedback date with the most influence over the entire vegetative growth period. Results indicated that the best overall match between modeled and actual biomass accumulation was obtained when feedback data were collected relatively late in the leaf vegetative growth period. Actual and modeled leaf number accumulation were not significantly different for three different feedback dates.

# AN EVALUATION OF TWO FEEDBACK VERSIONS OF THE CERES- MAIZE MODEL

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## INTRODUCTION

The objectives of this study were to determine when feedback data should be collected and to determine if more accurate yield estimates are obtained using feedback data. Results from testing two feedback versions on six data sets indicated that feedback data collected later in the leaf growth period provided a better overall match between modeled and actual biomass accumulation. Modeled estimates of yield and kernel weight were significantly improved using a second feedback model version that adjusts yield components based on the feedback data.

The CERES-Maize model simulates daily values for crop characteristics such as number of leaves per plant, total plant leaf area, leaf weight, stalk weight, and grain weight. The values of these characteristics represent the simulated crop growth during the growing season. If the model is used to forecast or estimate corn yield for a specific sample plot, then based on a multivariate t-test, early season values of modeled characteristics should statistically equal early season values of plot measurements. Equality between model and observed values may not occur for a number of reasons. The model does not address crop growth factors such as weeds, insects, disease, or nutrients. The weather, soils, variety, and management data used as model inputs may not be correct, or some parameters in the model may not be correct for a particular sample plot. Feedback data can be incorporated into the model to partially correct these inadequacies. The feedback model will adjust the simulated growth and development to statistically equal the observed crop growth and development on the feedback date or dates. This should help improve the accuracy of the final yield forecast or estimate.

The CERES-Maize model was developed primarily by Dr. J. T. Ritchie and Dr. Jim Kiniry, Agricultural Research Service, Temple, Texas. Two feedback versions were created from the June 1984 CERES-Maize model. The first version adjusts the modeled number of leaves and vegetative biomass to statistically equal the mean observed plot measurements on some feedback date prior to the end of leaf growth. A second version contains the same feedback algorithms as the first and also adjusts the modeled yield components, number of kernels per plant and kernel weight.

This report describes the two feedback versions of the CERES-Maize model, presents six test data sets, and reviews analysis results. Conclusions regarding these feedback procedures and recommendations for future feedback work are made. Appendix A describes the feedback algorithms in further detail. Appendix B contains detailed results from test runs of the two feedback versions, and Appendix C documents the feedback input data.

#### DESCRIPTION OF FEEDBACK PROCEDURE

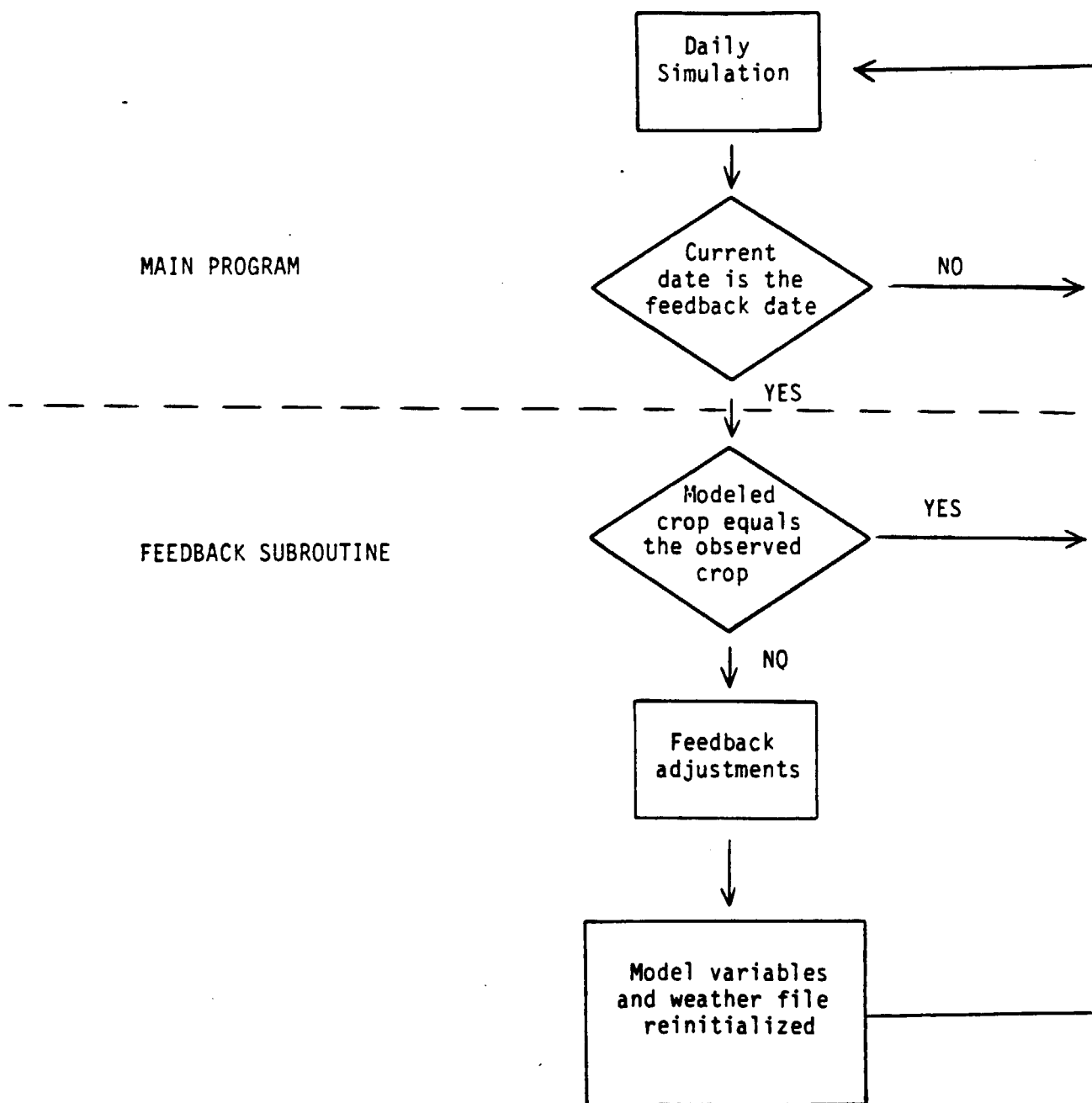
Both feedback versions of CERES-Maize are designed to modify the modeled growth and development of the crop so that model values statistically equal the mean observed number of leaves and vegetative biomass on the date of feedback prior to the end of leaf growth. Leaf growth refers to the period from crop emergence to near tasseling when new leaves are appearing and stalk and leaf weight are accumulating. Leaf number is the total number of leaf tips that have emerged prior to the feedback date and includes senesced leaves. Vegetative biomass is the total dry weight of stalks and leaves. The second feedback version makes additional adjustments to the number of kernels per plant and kernel weight based on the leaf number and vegetative biomass data.

Figure 1 presents the major steps of the feedback process for both model versions.

- STEP 1: Simulated growth and development occurs for each day of the growing season.
- STEP 2: After each day's simulated growth, the program checks if the current simulated day is the feedback date. If yes, the program branches to the feedback subroutine.
- STEP 3: The feedback subroutine conducts a multivariate  $T^2$  test to determine if the modeled number of leaves per plant and vegetative biomass per plant statistically equal observed values. Statistical equality occurs when the  $T^2$  test is not rejected (see appendix A).
- STEP 4: If statistical equality does not occur, adjustments to several internal model parameters and variables are calculated by the feedback algorithms.
- STEP 5: Certain model variables are reinitialized to their appropriate values for the crop at emergence.

The simulation is then repeated from the first day after emergence. When the feedback date is again reached, the feedback procedure is repeated. Iterations continue until the modeled number of leaves and vegetative biomass statistically equal the observed measurements. After equality occurs, the regular simulation continues until the simulated crop is mature. Appendix A provides further details regarding steps 3 and 4. In the second feedback version, the modeled number of kernels per plant and kernel weight are also adjusted.

Figure 1--  
General flow chart of feedback version of CERES-Maize model



## METHODS

Six data sets containing number of leaves per plant and vegetative biomass per plant on various dates prior to tasseling were used for testing the feedback versions of CERES-Maize. These data were collected during a nitrogen rate field experiment conducted by C. Allan Jones at Temple, Texas in 1981 and 1982 (unpublished data). (Table 1) The planting dates were April 28, 1981, and March 1, 1982.

Table 1: Test data set information concerning the year of collection, feedback day, amount of nitrogen applied, plant population, and yield

Data set	year	Nitrogen (kg/ha)	Plant pop. (plants/m <sup>2</sup> )	Sowing date	Julian feedback dates
1	1981	0	5.95	118	138, 148, 160
2	1981	40	5.95	118	138, 148, 160
3	1981	240	5.85	118	138, 148, 160
4	1982	0	5.88	60	96, 118, 131
5	1982	80	5.84	60	96, 118, 131
6	1982	240	5.88	60	96, 118, 131

One simulation model run was completed for each data set without using any feedback data. The model outputs corresponding to the three data sets within each year were very similar since the only difference between model inputs was plant population. The simulation model does not account for the effects of nitrogen. Next a separate model run employing the first feedback version was conducted for each of three feedback dates for each data set. Finally, a single model run was made using the second version that adjusts the yield components as well as leaf number and vegetative biomass. This model run employed feedback data from the third feedback date only. These five feedback options are identified in this report as No Feedback, 1<sup>st</sup> Date, 2<sup>nd</sup> Date, 3<sup>rd</sup> Date, and 3<sup>rd</sup> Date-V2, where the V2 indicates the second feedback procedure. The observed and modeled data are summarized in appendix tables 1-6. The special model inputs required for these feedback versions are documented in Appendix C.

## RESULTS AND DISCUSSION

The first objective of the analysis was to determine when feedback data should be collected to produce the best overall match between modeled and observed vegetative growth. The feedback procedure forces modeled variables to statistically equal the observed data on the feedback date. How well modeled and observed data agree on other dates may be dependent on when the feedback data were collected. Data collected as late as possible would appear best intuitively, but with the many plant and environment interactions within the model an earlier feedback day may be just as reliable. Sums over three feedback days of absolute differences between modeled and observed values for leaf number and vegetative biomass are presented in tables 3 and 4.

These sums were obtained from the data presented in appendix tables 1-6. For example, the sum of the absolute leaf number differences (2.8 in table 3) using feedback data from the first date for data set 1 is calculated in table 2.

Table 2: Example for calculating the sum of the absolute difference between modeled and observed leaf number from three observation dates

Julian date	Days from sowing	Modeled leaf number	Observed leaf number	Absolute difference
138	20	7	7.4	0.4
148	30	11	12.2	1.2
160	42	16	17.2	<u>1.2</u>
Sum				2.8

The observed value was 7.4 leaves on Julian day 138 (1<sup>st</sup> Date) which was 20 days after planting. The feedback version used this data to produce 7, 11, and 16 leaves on the three observation dates. These three modeled values were subtracted from the observed counts on their respective dates. The absolute differences were then summed. The total error over these three dates was 2.8 leaves.

These sums were an indication of the accuracy of the model estimated values of these variables over all three days. A smaller sum indicated more accurate estimates. Although the three observation dates (feedback days) were different in 1981 and 1982, the crops were at approximately the same developmental stage for corresponding visits, so they are roughly comparable.



A non-parametric multiple comparison test based on rank sums (Wilcoxon and Wilcox 1964) was used to test for significant differences between all possible pairs of sums for the three feedback days. The three sums of absolute differences for each data set were ranked, and rank sums were obtained for each feedback option. These rank sums were used to test for significant differences. The ranks and their sums are presented in tables 3 and 4 for leaf numbers and vegetative biomass.

Table 3: Sums of absolute leaf number difference (and associated ranks within data sets) for three feedback observation dates

Data set	:	Feedback option		
		1st Date	2nd Date	3rd Date
1	:	2.8 ( 3.0)	1.6 ( 2.0)	1.0 ( 1.0)
2	:	1.4 ( 3.0)	1.2 ( 1.5)	1.2 ( 1.5)
3	:	0.5 ( 2.0)	0.5 ( 2.0)	0.5 ( 2.0)
4	:	0.6 ( 1.0)	0.8 ( 2.0)	1.4 ( 3.0)
5	:	1.4 ( 2.5)	0.8 ( 1.0)	1.4 ( 2.5)
6	:	0.7 ( <u>1.5</u> )	0.7 ( <u>1.5</u> )	1.7 ( <u>3.0</u> )
	:	(13.0)	(10.0)	(13.0)

The critical difference between sums of ranks is 7.1 (  $\alpha = .10$ ) for comparing all possible pairs of feedback options.

The non-parametric test on the sums of absolute leaf number differences (table 3) indicated no significant differences among the three feedback options. This suggested a similarity between observed and modeled leaf numbers regardless of when the feedback data were obtained.

The results of the non-parametric test on the sums of absolute vegetative biomass differences (table 4) indicate that the sums from the 3<sup>rd</sup> Date option are almost significantly different from the sums for the 1<sup>st</sup> Date at  $\alpha = .10$ . No other significant differences between dates were detected. These results suggested that feedback data collected for the 3<sup>rd</sup> Date option, which was collected about 10-15 days

before the end of leaf growth, provided slightly better overall match to observed biomass than using feedback data collected on the first feedback date. Feedback data collected from older plants were more important for adjusting modeled biomass accumulation by the feedback version than data collected from younger plants.

Table 4: Sums of absolute biomass difference (and associated ranks within data set) for three feedback observation dates

Data set	:	Feedback option		
		1st Date	2nd Date	3rd Date
1	:	21.2 ( 3.0)	18.5 ( 2.0)	11.7 ( 1.0)
2	:	42.1 ( 3.0)	14.7 ( 1.0)	17.1 ( 2.0)
3	:	24.8 ( 3.0)	11.4 ( 2.0)	11.3 ( 1.0)
4	:	10.8 ( 2.0)	12.8 ( 3.0)	4.4 ( 1.0)
5	:	9.5 ( 2.0)	8.6 ( 1.0)	10.0 ( 3.0)
6	:	24.7 ( <u>3.0</u> )	18.4 ( <u>2.0</u> )	15.8 ( <u>1.0</u> )
	:	(16.0)	(11.0)	( 9.0)

The critical difference between sums of ranks is 7.1 ( $\alpha = .10$ ) for comparing all possible pairs of feedback options.

The second objective of the analysis was to determine if using feedback data provided more accurate estimates of corn yield and the yield components than not using feedback data. Tables 5, 6 and 7 contain the observed yield, observed mean number of kernels per plant, and individual kernel weight respectively for each data set, and the differences from the values simulated by each feedback option. A non-parametric multiple comparison test based rank sums (Wilcoxon and Wilcox, 1964) was used to make pairwise comparisons between each of the differences from the four feedback options and the No Feedback option. That is, the differences from four feedback options (treatments) were tested against the No Feedback option (control). The differences for the four feedback option sums should be smaller than the No Feedback option sum if feedback provided more accurate estimates.

The results from table 5 indicate that feedback under version 2 significantly improved the simulated yield estimate. The average error for the six data sets was 472 kg/ha or 8% of the average observed corn yield. In each data set the simulated estimate from feedback version 2 was closest to the final observed yield.

The results from table 6 indicated that none of the feedback options had significantly smaller absolute differences from the observed number of kernels than did the No Feedback option. However the second feedback version using the yield component adjustments (3<sup>rd</sup> Date - V2) reduced the extreme differences in data sets 4 and 6 as compared to the other options. Also, the maximum absolute difference with the second feedback version (113.8) was substantially smaller than the maximum differences for the first version. These results suggested that the second version had an advantage over the first, although further developmental work is needed.

Regarding kernel weights, the second feedback version using the yield component adjustments produced significantly smaller differences from the observed values than did the No Feedback option (table 7). None of the other feedback options produced significantly smaller differences. The results indicate that using observed data with the first feedback version had very little effect on kernel weight. The kernel weight differences changed very little from those obtained with no feedback.

The analyses of the simulated yield components indicated that the second feedback version which adjusted the kernel number and kernel weight directly, has some advantages over the first feedback version. The first version only adjusted simulated growth and development during leaf growth (prior to tasseling). Large increases and decreases in plant size were obtained from the application of this procedure (appendix tables 1-6). It was anticipated that changing the modeled plant size would have a corresponding effect on yield. However, these feedback induced changes did not produce significant improvements in yield component estimates. An extreme example was data set 4 (appendix table 4). Biomass was reduced by over 60% through feedback with the first version (all dates), but yield changed less than 10%. This suggests the model is not sensitive enough to the size of the plant during reproductive growth. Model problems need to be eliminated before feedback can function properly and consistently under all growing conditions.

## CONCLUSIONS AND RECOMMENDATIONS

Two feedback versions of the CERES-Maize model were developed that forced the modeled number of leaves and vegetative biomass to statistical equality with observed mean values made on a feedback visit during leaf growth. The best agreement with actual biomass accumulation was obtained if feedback data were collected on older plants later in the leaf growth period. The overall match with actual leaf number accumulation was not affected by the date or size of the plants when feedback data were collected.

Table 5: Observed yield (kg/ha), differences from observed values, and ranks of absolute differences for the five feedback options applied to the six data sets.

Data set	Observed yield (kg/ha)	No feedback	Differences: simulated minus observed value (associated ranks)				
			Feedback option				
			Version 1		Version 2		
			1st	2nd	3rd	3rd	
			Date	Date	Date	Date-V2	
1	5168	4342 (4.0)	3722 (3.0)	3231 (2.0)	4364 (5.0)	1241 (1.0)	
2	5111	4399 (5.0)	2916 (2.0)	3704 (4.0)	3542 (3.0)	2199 (1.0)	
3	6090	3406 (5.0)	1397 (2.0)	2486 (4.0)	2271 (3.0)	-1031 (1.0)	
4	1992	6070 (4.0)	5751 (3.0)	6506 (5.0)	5440 (2.0)	465 (1.0)	
5	6223	1827 (2.0)	1850 (3.0)	2323 (5.0)	1855 (4.0)	504 (1.0)	
6	11620	-3558 (5.0)	-3534 (4.0)	-3349 (3.0)	-2589 (2.0)	-549 (1.0)	
ave.	6034	2748	2017	2484	2481	472	
rank sum		(25.0)	(17.0)	(23.0)	(19.0)	(6.0)	

The critical difference between the sum of ranks is 11.8 for a one way test to determine if any of the feedback options produced significantly smaller absolute differences than no feedback ( $\alpha = .05$ )

Table 6: Mean observed number of kernels per plant, kernel number differences from observed values and ranks of absolute difference for the five feedback options applied to the six data sets

Data set	Observed number of kernels on plant	No feedback	Differences: simulated minus observed value (associated ranks)				
			Feedback option				
			Version 1		Version 2		
			1st Date	2nd Date	3rd Date	3rd Date-V2	
1	389.5	117.7 (4.0)	84.8 (3.0)	60.3 (2.0)	119.2 (5.0)	8.5 (1.0)	
2	386.9	120.3 (5.0)	47.9 (2.0)	85.2 (4.0)	76.8 (3.0)	31.6 (1.0)	
3	446.8	68.4 (4.0)	-39.1 (3.0)	20.4 (2.0)	8.9 (1.0)	-113.8 (5.0)	
4	153.7	282.0 (4.0)	270.3 (3.0)	311.9 (5.0)	253.6 (2.0)	43.9 (1.0)	
5	424.7	13.3 (3.0)	-0.7 (2.0)	39.2 (4.0)	-0.6 (1.0)	-45.8 (5.0)	
6	674.4	-238.7 (3.0)	-252.6 (5.0)	-243.1 (4.0)	-188.2 (2.0)	-17.3 (1.0)	
ave.	412.7	60.5	18.4	45.7	45.0	-15.5	
rank sum		(23.0)	(18.0)	(21.0)	(14.0)	(14.0)	

The critical difference between the sum of ranks is 11.8 for a one way test to determine if any of the feedback options produced significantly smaller absolute differences than no feedback (  $\alpha = .05$  )

Table 7: Mean observed kernel weight (g), differences from observed values, and ranks of absolute difference for the five feedback options applied to the six data sets.

Data set	Observed kernel weight (g)	No feedback	Differences: simulated minus observed value (associated ranks)				
			Feedback option				
			Version 1		Version 2		
			1st Date	2nd Date	3rd Date	3rd Date-V2	
1	.223	.092 (4.0)	.092 (4.0)	.091 (2.0)	.092 (4.0)	.048 (1.0)	
2	.222	.093 (5.0)	.088 (2.0)	.092 (3.5)	.092 (3.5)	.072 (1.0)	
3	.233	.082 (5.0)	.081 (3.0)	.081 (3.0)	.081 (3.0)	.027 (1.0)	
4	.225	.090 (5.0)	.086 (4.0)	.085 (2.5)	.085 (2.5)	-.013 (1.0)	
5	.257	.058 (2.0)	.069 (4.5)	.059 (3.0)	.069 (4.5)	.047 (1.0)	
6	.311	.004 (1.0)	.015 (3.5)	.015 (3.5)	.005 (2.0)	-.025 (5.0)	
ave.	.245	.070	.072	.071	.071	.026	
rank:		(22.0)	(21.0)	(17.5)	(19.5)	(10.0)	
sum :							

The critical difference between the sum of ranks is 11.8 for a one way test to determine if any of the feedback options produced significantly smaller absolute differences than no feedback (  $\alpha = .05$  )

Analysis on six test data sets indicated that statistically forcing modeled leaf number and vegetative biomass to closely match observed measurements did not provide significantly improved model estimates of yield or yield components. Improved estimates of yield and kernel weight were only obtained from a second feedback version where additional adjustments were made directly on the yield components. Further basic research by plant scientists and development of these yield component adjustments by the modelers are needed to determine if these adjustments employed in the models are physiologically reasonable.

Finally, feedback is only designed and intended to modify modeled crop growth when some unusual growth situation is affecting the crop being modeled. Feedback can slow down or speed up development and increase or decrease growth. However, feedback cannot correct problems due to faulty model philosophy, logic, or relationships. Those problems have to be addressed first before feedback will be of any help.

At the present time the CERES-Maize model is not ready for a pilot test or operational use. If and when the research scientists have demonstrated that model problems have been corrected, then applicability of the model should be reexamined. SRS should not fund further basic research but should keep advised of any model development progress.

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## APPENDIX A

### The feedback algorithms

The major aspects of the feedback procedure were to test if the modeled crop statistically equaled the observed crop, to determine if adjustments were needed for leaf number, vegetative biomass, and yield components, and then to make the adjustments. This appendix describes these steps.

#### Testing if the modeled crop equals the observed crop

The feedback subroutine conducts a multivariate  $T^2$  test to determine if the modeled leaf number and biomass values satisfactorily equal the mean observed values. If there is some error associated with the observed values, the model does not have to exactly match the observed values in order to achieve a statistical equality. Assuming the observed values are sample means from a multivariate normal distribution, the  $T^2$  test is used to determine if equality exists. The  $T^2$  value is calculated based on the differences between modeled and observed values and input sample variances. If the calculated  $T^2$  value is not significant, no adjustments are made, and the model resumes the simulation for the next day.

#### Determining the needed feedback adjustments

If the multivariate  $T^2$  value is significant, then separate  $T^2$  tests are conducted for each of the two variables to determine which one is significant (Bolch and Huang, p. 83). The decision rule for adjustments based on these separate  $T^2$  tests is indicated in appendix figure 1. Adjustments for only one of the two feedback variables are made in each feedback iteration.

Parameters affecting modeled number of leaves are adjusted before the biomass parameters. The number of leaves reflects the stage of development of corn. The modeled crop needs to be at the same stage of development as the observed crop before a comparison to the observed biomass is meaningful. Adjustment of the biomass parameter is only made if there is a satisfactory match of modeled and observed number of leaves ( $T1SQ < SIGT$ ) and the  $T^2$  value for the biomass difference is larger than the  $T^2$  value for the difference in number of leaves ( $T2SQ > T1SQ$ ). The only exception is if an adjustment for modeled number of leaves is suggested by the criteria, but the difference between the modeled and observed number of leaves is less than 0.50. In that case, no smaller difference can be obtained (since the modeled number is always an integer). An adjustment to the biomass parameter could still be made if needed.

Appendix Figure 1: Decision criteria for feedback adjustments

		T1SQ < SIGT	T1SQ > SIGT
T2SQ < T1SQ		Adjust number	Adjust number
		of leaves	of leaves
T2SQ > T1SQ		Adjust biomass	Adjust number
			of leaves

SIGT = Significant  $T^2$  value at specified  $\alpha$

T1SQ =  $T^2$  value for testing if modeled leaf number is significantly different from the mean observed number

T2SQ =  $T^2$  value for testing if modeled vegetative biomass is significantly different from the mean observed biomass

#### Adjusting leaf number

The modeled number of leaves on a certain day is determined by the accumulated number of heat units since emergence and the phyllochron interval (PHINT). The number of heat units in a day is defined as:

$$DTT = \frac{TEMPMX + TEMPMN}{2} - TBASE$$

Where

- DTT = Daily heat units
- TEMPMX = Daily maximum temperature ( $^{\circ}\text{C}$ )
- TEMPMN = Daily minimum temperature ( $^{\circ}\text{C}$ )
- TBASE = Base temperature =  $8^{\circ}\text{C}$

The phyllochron interval is the basic number of heat units required for each new leaf. A value of 40 is used for all varieties by the model except for leaves 2-5. These leaves require less than 40 heat units.

Moving the emergence date earlier or later will cause more or fewer heat units to accumulate by the feedback date, and consequently more or fewer leaves on the modeled plant. The emergence date is a candidate for adjustment since modeling emergence is one of the weaker aspects of the model. The maximum number of days the emergence date can be changed is dependent upon the earliest and latest possible sowing dates (ISOW1 and ISOW2). If the feedback version of CERES-Maize were ever used operationally by the Statistical Reporting Service in conjunction with the Corn Objective Yield (OY) survey, the initial field visit would probably be made several months after planting. In that case, it is certainly possible that the farmer will not remember the exact planting date for the sample field. The variables ISOW1 and ISOW2 would indicate the possible range in planting dates for a certain OY sample. If the planting date is known exactly, then they should both equal the input planting date.

If the observed mean number of leaves is significantly greater than the modeled number of leaves, then an earlier modeled emergence date is needed. The earliest possible date is 5 days after ISOW1. Similarly, if the observed number of leaves is less than the modeled number of leaves, then a later modeled emergence date is needed. The latest possible emergence date is at least 5 days after the original emergence date. It may be more than 5 days later if ISOW2 is more than 5 days after the original emergence date. A new emergence date is then determined to be within this range of dates so the required number of heat units will accumulate by the feedback date. If changing the emergence date up to these limits cannot produce the desired number of leaves, then the next step is to adjust the PHINT. Otherwise, the simulation starts over at the new emergence date. The emergence date is only adjusted on the first iteration. If the model still does not match the observed number of leaves satisfactorily, only PHINT and the daily temperature will be adjusted on further iterations.

After a new emergence date is determined, the modeled plant may still need more or fewer leaves on the feedback date. In that case, PHINT is adjusted. If more leaves are needed, PHINT will be reduced so leaves will appear more rapidly. If fewer leaves are needed, PHINT will be increased so leaves will appear more slowly. Reasonable values of PHINT range from 35 to 45 heat units.

The factor PHINTF is calculated in the feedback algorithms as an additional adjustment to PHINT. The limits for PHINTF are currently set at - 5 and + 5. If the calculated value is outside of this range, then PHINTF is set at the appropriate maximum adjustment and additional adjustments are made to the daily temperatures. Otherwise the simulation starts over at the new emergence date with the new PHINT value. This new value is used for all simulated leaves in the leaf growth period.

The daily temperatures are the last variables that may be adjusted in order to force the modeled number of leaves to statistically equal the observed number. It is assumed the temperature data being used for the simulation were not obtained at the canopy of the observed crop, but at some weather station, possibly 50 miles away, and consequently contain some error. A temperature adjustment, the feedback temperature factor (FBTF), is calculated by the feedback algorithms. Increasing or decreasing both the maximum and minimum temperatures by FBTF should provide the required number of heat units to produce the observed number of leaves. The current feedback version only adjusts temperature using FBTF from emergence until the feedback date. The limits for FBTF are set at  $-3^{\circ}\text{C}$  and  $+3^{\circ}\text{C}$ . If the calculated value of FBTF is outside this range on the first feedback iteration, FBTF is set to the appropriate limit. Possibly this adjustment will provide statistical equality between modeled and observed number of leaves. If there is not an acceptable match on the second iteration, this indicates that even after adjusting the emergence date, PHINT, and the daily temperatures to their limits, the model still does not satisfactorily equal the mean observed leaf numbers on the feedback date. In that case, there is some problem with the input data, the feedback date, or the model that makes a satisfactory match impossible within the limits set for the adjustment variables. Normally, appropriate values for the emergence date, the phyllochon interval, and the temperature adjustment are obtained after only one iteration through the feedback calculations.

#### Adjusting modeled vegetative biomass

The biomass feedback adjustment is not made unless the modeled crop already equals the observed number of leaves. The leaf number agreement may be due to previous feedback iterations or possibly the model agreed with the observed leaf number without any feedback adjustments. A match of the leaf numbers indicates that the modeled and observed crops are at approximately the same developmental stage. Only then are comparisons of modeled and observed biomass values meaningful.

The biomass adjustment is based on a very simple equation. The feedback stress factor (FBSF) is calculated as:

$$\text{FBSF} = (\text{FBM}/(\text{LFWT} + \text{STMWT})) * \text{FBSF}$$

where

FBM	= mean observed vegetative biomass (g)
LFWT	= modeled leaf biomass (g)
STMWT	= modeled stalk biomass (g)

The ratio of the observed to modeled vegetative biomass is used as a multiplicative adjustment to the previous FBSF (initial value of FBSF = 1). This new FBSF is then used as a multiplicative adjustment to the amount of leaf area growth each day. More leaf area growth produces more biomass, and less leaf area growth produces less biomass. These calculations only occur during the leaf growth period prior to tasseling.

It usually takes 2 - 3 iterations through this calculation before the modeled and observed biomass values on the feedback date match satisfactorily.

#### Adjusting yield components

In the second feedback version, the number of kernels per plant and the kernel weight are adjusted using FBSF. The number of kernels per plant (GPP) is calculated in the model on the first day of grain fill as:

$$GPP = G2 * EARWT$$

where  $G2$  = variety specific constant  
 $EARWT$  = weight of ear shoot (g)

Ear shoot weight is accumulated between the end of leaf growth, which is around tasseling, and the beginning of grain fill. In the second feedback version, FBSF was used as a third multiplicative factor in the GPP equation above. The other yield component, kernel weight, is accumulated during the grain fill stage. The daily grain growth (GROGRN) was adjusted in the second feedback version as follows:

$$GROGRN = GROGRN * (0.4 + 0.6 * FBSF), FBSF < 1.0$$

These yield component adjustments are designed to continue the stress effect detected during vegetative growth into the grain fill period. Preliminary testing indicated that the modeled grain weights tended to be too large, so FBSF is used only to reduce grain growth.

## APPENDIX B

Summary data for test data sets including the observed and modeled values for three variables on different feedback dates.

Appendix table 1: Summary data for data set 1

Type	Leaf number on feedback day				Vegetative biomass (g) on feedback day			Yield (kg/ha)
	138	148	160		138	148	160	
Observed	7.4	12.2	17.2		1.9	14.1	66.7	5168
No Feedback	7	11	16		3.4	22.5	69.1	9510
1st Date	7	11	16		1.9	12.0	47.6	8890
2nd Date	8	12	18		2.4	13.4	49.4	8399
3rd Date	8	12	17		4.1	22.6	67.7	9532
3rd Date - V2	8	12	17		4.1	22.6	67.7	6409

Appendix table 2: Summary data for data set 2

Type	Leaf number on feedback day				Vegetative biomass (g) on feedback day			Yield (kg/ha)
	138	148	160		138	148	160	
Observed	7.6	12.4	17.6		1.9	17.3	71.2	5111
No Feedback	7	11	16		3.4	22.5	69.1	9510
1st Date	8	12	17		1.8	9.6	36.9	8027
2nd Date	8	12	18		3.1	17.1	57.9	8815
3rd Date	8	12	18		5.1	28.2	76.2	8653
3rd Date - V2	8	12	18		5.1	28.2	76.2	7310

Appendix table 3: Summary data for data set 3

Type	Leaf number on feedback date			Vegetative biomass (g) on feedback date			Yield (kg/ha)
	138	148	160	138	148	160	
Observed	7.8	12.3	18.0	2.2	15.6	64.3	6090
No Feedback	7	11	16	3.4	22.5	69.6	9496
1st Date	8	12	18	2.1	11.4	43.8	7487
2nd Date	8	12	18	2.7	15.1	53.9	8576
3rd Date	8	12	18	4.0	22.2	67.2	8361
3rd Date - V2	8	12	18	4.0	22.2	67.2	5059

Appendix table 4: Summary data for data set 4

Type	Leaf number on feedback date			Vegetative biomass (g) on feedback date			Yield (kg/ha)
	96	118	131	96	118	131	
Observed	5.4	10.2	14.0	0.3	6.6	17.0	1992
No Feedback	8	14	18	4.2	32.4	77.4	8062
1st Date	5	10	14	0.6	6.6	27.5	7743
2nd Date	6	10	14	1.2	7.4	28.1	8498
3rd Date	6	11	14	0.5	3.8	15.6	7432
3rd Date - V2	6	11	14	0.5	3.8	15.6	2457

Appendix table 5: Summary data for data set 5

Type	Leaf number on feedback date				Vegetative biomass (g) on feedback date			Yield (kg/ha)
	96	118	131		96	118	131	
Observed	6.8	12.2	16.6		1.3	14.0	59.0	6223
No Feedback	8	14	18		4.2	32.4	77.6	8050
1st Date	7	13	17		2.5	19.7	61.6	8073
2nd Date	7	12	17		2.1	13.9	51.3	8546
3rd Date	7	13	17		2.5	20.1	61.7	8078
3rd Date - V2	7	13	17		2.5	20.1	61.7	6727

Appendix table 6: Summary data for data set 6

Type	Leaf number on feedback date				Vegetative biomass (g) on feedback date			Yield (kg/ha)
	96	118	131		96	118	131	
Observed	6.8	12.7	17.2		1.3	22.1	82.5	11620
No Feedback	8	14	18		4.2	32.4	77.4	8062
1st Date	7	13	17		2.5	19.7	61.4	8086
2nd Date	7	13	17		2.8	22.7	66.2	8271
3rd Date	8	13	17		4.2	31.9	79.4	9031
3rd Date - V2	8	13	17		4.2	31.9	79.4	11071



## APPENDIX C

### Feedback input data

Appendix table 7 documents the special input data required to run the feedback model. Documentation of the other model inputs can be obtained from the model developers or the author of this report.

A separate set of input values was established for each feedback date of each data set used in the analysis for this study. ISOW1 and ISOW2 were assigned values one day prior and one day after the reported sowing date. The mean observed number of leaves and amount of vegetative biomass per plant for the respective feedback date were read as FNLT and FBM. Individual plant data were not available, so the variances and covariance information were estimated from other sources. It was assumed measurements were made on 15 individual plants (NOBS). The significant  $T^2$  value was assigned to be 5.945, using a significance level of  $\alpha = .10$ .

Appendix table 7: Feedback input data

Variable Name	Description
ISOW1	Earliest possible sowing date (day of year)
ISOW2	Latest possible sowing date (day of year)
KDAY	Feedback date (day of year)
FNLT	Mean observed number of leaf tips per plant
FBM	Mean observed vegetative biomass per plant (g)
A1	Variance of leaf tip numbers
A2	Variance of vegetative biomass values
C11	Value from inverse of variance - covariance matrix $\frac{1}{S}$
C12	Value from inverse of variance - covariance matrix $\frac{1}{S}$
C22	Value from inverse of variance - covariance matrix $\frac{1}{S}$
SIGT	Significant $T^2$ value dependent on number of observations and desired significance level
NOBS	Number of sampled plants

$$\frac{1}{S} = \text{Inverse of variance - covariance matrix} = S^{-1} = \begin{bmatrix} C11 & C12 \\ C12 & C22 \end{bmatrix}$$

$$\text{where } S = \begin{bmatrix} A1 & COV \\ COV & A2 \end{bmatrix}$$

COV = Covariance (NLT, BM)  
 NLT = Number of leaf tips  
 BM = Vegetative biomass